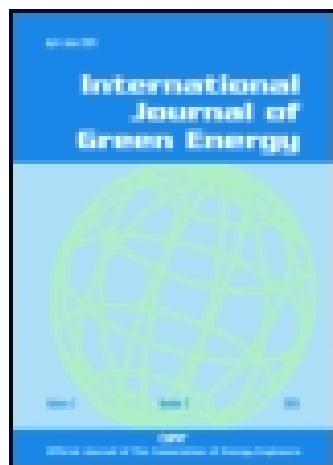


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## International Journal of Green Energy

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/ljge20>

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Published online: 04 Dec 2008.

To cite this article: Erin Searcy & Peter C. Flynn (2008) Processing of Straw/Corn Stover: Comparison of Life Cycle Emissions, International Journal of Green Energy, 5:6, 423-437

To link to this article: <http://dx.doi.org/10.1080/15435070802498010>

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## PROCESSING OF STRAW/CORN STOVER: COMPARISON OF LIFE CYCLE EMISSIONS

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*The LCA emissions from four renewable energy routes that convert straw/corn stover into usable energy are examined. The conversion options studied are ethanol by fermentation, syndiesel by oxygen gasification followed by Fischer Tropsch synthesis, and electricity by either direct combustion or biomass integrated gasification and combined cycle (BIGCC). The greenhouse gas (GHG) emissions of these four options are evaluated, drawing on a range of studies, and compared to the conventional technology they would replace in a western North American setting. The net avoided GHG emissions for the four energy conversion processes calculated relative to a “business as usual” case are 830 g CO<sub>2</sub>e/kWh for direct combustion, 839 g CO<sub>2</sub>e/kWh for BIGCC, 2,060 g CO<sub>2</sub>e/L for ethanol production, and 2,440 g CO<sub>2</sub>e/L for FT synthesis of syndiesel. The largest impact on avoided emissions arises from substitution of biomass for fossil fuel. Relative to this, the impact of emissions from processing of fossil fuel, e.g., refining of oil to produce gasoline or diesel, and processing of biomass to produce electricity or transportation fuels, is minor.*

**Keywords:** Renewable energy; Life cycle analysis; Agricultural residues; Lignocellulosic ethanol; Fisher Tropsch; BIGCC

## INTRODUCTION

The world is actively seeking sources of usable energy that have a reduced emission of greenhouse gases (GHG). This effort to select renewable energy sources is challenging because there are a number of alternative primary sources of energy (e.g., wind, solar, hydro, and many types of biomass) and a large number of processing routes to convert the primary energy source into a form useful to humans. Biomass, for example, is available as urban waste, mill residues, forest harvest residues, the whole forest, agricultural residues such as straw or corn stover, purpose-grown crops, and animal manures. Lignocellulosic biomass can be converted to ethanol by direct lignocellulosic fermentation or gasification and fermentation of the gas, to diesel by oxygen gasification followed by the Fischer Tropsch process, to electricity by either direct combustion or integrated gasification and combined cycle (BIGCC), and to a highly oxygenated bio-oil by pyrolysis.

As the extent of renewable energy increases as a fraction of total energy usage, it becomes more critical to make wise choices about the type of primary energy and the processing route, to ensure that the most economic alternatives to fossil fuel are chosen.

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Failure to do this will burden society with needlessly high-cost energy or alternatively achieve a lower reduction of GHG for the same incremental expenditure on energy.

Many or all forms of renewable energy are more expensive than fossil fuel. The appropriate economic criterion for evaluating technologies is minimizing the cost of achieving the desired social goal, which is a reduction in GHG that would otherwise enter the atmosphere. The incremental cost of the energy relative to a fossil fuel alternative divided by the reduction in GHG expressed as CO<sub>2</sub>-equivalent emissions (denoted as CO<sub>2</sub>e herein) is a measure of the social cost of the selection of a renewable energy process: how much extra does it cost to avoid a tonne of CO<sub>2</sub>e in the atmosphere? This cost must be borne by society, typically by consumers or taxpayers. To determine this measure, one must determine the life cycle reduction in emissions and the incremental cost associated with a renewable energy process compared to its fossil fuel alternative. In this work we assess the comparative reduction in emissions for one abundant type of biomass from four potential processing routes, drawing on a wide range of studies.

We focus on agricultural residues in the form of straw and corn stover, which are widely available on an annual basis because of the growth of cereal crops for human consumption and animal feed. Agricultural residues are available in significant quantities in areas where growth of grain crops is concentrated, e.g., the U.S. Midwest corn belt and the areas of wheat and barley cultivation in the western United States and Canada. Table 1 shows the properties of recovered straw and corn stover that are typical of North American farming practices. Straw/stover is typically recovered after grain harvest by a separate pass over the field, although there is development work aimed at simultaneous recovery of both grain and straw (Beaudry-Losique 2007). Large round or square bales are the usual form of recovery, both transportable by truck.

Our work is focused on four processing alternatives for straw/stover:

- Electrical power from the direct combustion of biomass with a conventional three-stage steam turbine cycle. The assumed technology is a circulating fluidized bed boiler like the one in use at the Alholmens 240 MW wood-fired power plant in Pietersaari, Finland (Flynn and Kumar 2005).
- Electrical power from air gasification of biomass followed by combined cycle power generation from the low-heating value gas.
- Ethanol from enzymatic hydrolysis of lignocellulose followed by microbial fermentation of produced sugars, with combustion of recovered lignin to meet plant energy needs and produce surplus power for sale.
- Diesel from oxygen gasification of biomass followed by a Fischer Tropsch (FT) processing plant designed to maximize the production of diesel. The plant therefore includes recycling of unreacted syngas and a wax cracker to convert long chain hydrocarbons back into a diesel fraction.

**Table 1** Straw and stover properties (Searcy et al. 2007).

MC, %	15
Hydrogen content, wt %	5.46
Bulk density, dry kg/m <sup>3</sup>	140
HHV, dry basis MJ/kg	18
LHV as is, MJ/kg	13.9
Transport form	Bale

In a previous work we have summarized available data on yields for these four alternatives (Searcy and Flynn 2008). Two cases for BIGCC were reported; this study is based on the BIGCC modified case. Note, however, that the quality of the technical and economic data varies widely for these four processing alternatives. Power production from biomass at very large scale is in commercial operation today (Flynn and Kumar 2005). Six commercial scale lignocellulosic ethanol plants are under construction in the United States, sponsored by the U.S. Department of Energy (DOE), but estimates or actual cost figures from these plants are not available (U.S. DOE 2008). Fischer Tropsch processing of biomass and BIGCC have not been implemented at a significant scale, and capital and operating cost estimates have a greater degree of uncertainty (Searcy and Flynn 2008).

## LIFE CYCLE ANALYSIS (LCA)

### Determining the “Business as Usual” Case

One key question in any analysis of the life cycle reduction in emissions from a renewable energy project as compared to a fossil fuel project is a determination of what is avoided if the renewable energy project proceeds; the avoided emissions are calculated relative to a “business as usual” case. This is location-specific, and in this study we consider a western North American location for the projects.

For biomass processing that uses electrical power imported from the grid (only the FT syndiesel case in this study), grid average emissions of CO<sub>2</sub>e/MWh are the appropriate measure of impact on emissions. Power to the North American grid comes from many sources, including lesser amounts from wind, hydro, and nuclear plants as well as gas and coal-fired thermal combustion plants. The grid average emissions per unit of power generation will vary from region to region based on this mix. In Alberta, Canada, grid average emissions are 761 g CO<sub>2</sub>e/MWh (Tampier et al. 2004), a value used in this study. However, for processes that export power to the grid, the appropriate measure of avoided emissions is based not on grid average emissions but rather on what “business as usual” power generation is displaced.

The “business as usual” source of electrical power in this study is a supercritical coal-fired power plant. A biomass-fired power plant in North America would typically be a base loaded plant, particularly if it were supported by revenue from carbon credits that reduced its marginal operating cost. Plants with a low marginal operating cost are typically dispatched 24/7, and would compete with coal-fired base load power plants. Our presumption in this study is that in a North American setting the building of an incremental biomass power plant would defer the same generation capacity from a new coal power plant.

For transportation fuel production the “business as usual” case in this study is reliance on conventional imported oil. North America as a whole is a net importer of oil, and production of transportation fuel from biomass is assumed to reduce import of oil rather than existing North American production. Ethanol is presumed to go into the gasoline pool as a blend, and hence gasoline from incremental oil refining is the “business as usual” case. The Fischer Tropsch case in this study is based on maximizing the yield of diesel fuel; hence diesel from incremental oil refining is the “business as usual” case.

### Scope of the LCA

The LCA analysis is focused on GHG emissions. We consider three major emissions thought to contribute to global warming: CO<sub>2</sub> from fossil fuels, CH<sub>4</sub>, and N<sub>2</sub>O (Furuholt,

1995; Mann and Spath, 1997). Although water vapor is also a GHG and accounts in the atmosphere for a substantial fraction of the GHG effect, it is not included in this study in the belief that it is short-lived in the atmosphere. Some research suggests that water vapor concentrations in the atmosphere are increasing due to human activity (see, for example, Santer et al. 2007), but the studies are limited in number and not sufficient to provide a net weighting factor, if any, to water emissions. Carbon emissions from biomass are not counted, since the presumption is that future crop growth will take up this carbon as new biomass. There is some ongoing debate about the GHG relative weighting to be applied to compounds; in this study we use 21 to equate the impact of CH<sub>4</sub> to the CO<sub>2</sub>e impact (kg CH<sub>4</sub>/kg CO<sub>2</sub>e), and 310 for N<sub>2</sub>O (Alberta Environment 2007).

The functional unit for the two electricity production cases is CO<sub>2</sub>e emissions per MWh of electricity. The functional unit for diesel production is CO<sub>2</sub>e emissions per liter of fuel, since the lower heating values (LHV) for diesel from petroleum and FT synthesis are comparable (Abbott et al. 2006; Laohalidanond et al. 2006), and the presumption is that the two sources of diesel achieve equal efficiency in the engine. The functional unit for ethanol is CO<sub>2</sub>e emissions per liter of fuel grade ethanol (Permolox 2008). The basis of emissions comparison to gasoline is the equivalence of 0.66 L of gasoline to 1 L of ethanol, based on an average lower heating value for gasoline of 32.0 MJ/L and for fuel grade ethanol of 21.1 MJ/L (ORNL 2007). This relationship reflects that distance traveled by a spark-ignition engine-propelled vehicle is proportional to the energy content of the fuel (MacLean et al. 2000). For the electrical power cases the boundary is the energy produced at the processing plant, i.e., power going into the transmission grid. This means that locational impacts of biomass vs. coal-fired power plants on transmission losses are ignored. For the transportation fuel cases the boundary is the combustion of the fuel in the engine, but we assume that differences in emissions associated with the distribution and retailing of transportation fuels are negligible.

The emissions related to energy use for the manufacture, construction, and decommissioning of processing facilities is not included in this study for two reasons. First, energy usage and emissions for manufacture, construction, and decommissioning is two to three orders of magnitude lower than the energy processed by the facility, and hence negligible in the overall analysis (Mann and Spath 1997; Tampier et al. 2004). This also applies to emissions associated with exploration and drilling activities associated with fossil fuels (Tyson 1993). The second reason to ignore emissions from the manufacture, construction, and decommissioning of processing facilities is that they are not substantially different between the “business as usual” and straw processing cases. For example, the usage of concrete and steel and the effort of construction would be virtually identical for the same size of power plant burning coal or straw.

When calculating carbon emissions from power generation, an oxidation factor of 0.99 is used as per the Intergovernmental Panel on Climate Change (IPCC) guidelines for calculating emissions inventories. This factor presumes that 1% of the fuel remains unoxidized. This factor is not applied in transportation fuel cases, where complete combustion is assumed.

### **Emissions from the Harvest and Transport of Straw/Stover**

Mann and Spath (1997) evaluated emissions from the harvesting of wood chips from purpose-grown crops. Tyson (1993) calculated emissions for a variety of lignocellulosic materials. However, Spatari et al. (2005) focus specifically on the recovery of agricultural residues, corn stover from eastern Canada. Table 2 shows both mass emissions and CO<sub>2</sub>e

**Table 2** CO<sub>2</sub> emissions from the harvest and transport over 100 km of one kg of straw/stover (Spatari et al. 2005).

Stressor	Air emissions (g/kg biomass)	Equivalent emissions (g/kg biomass)	Air emissions (g/kg biomass/100 km)	Equivalent emissions (g/kg biomass/100km)
CO <sub>2</sub>	44.7	44.7	3.94	3.94
CH <sub>4</sub>	0.14	2.95	0.0156	0.329
N <sub>2</sub> O	0.116	36.1	0.00371	1.15
Total CO <sub>2</sub> e (g/kg dry biomass)		83.8	Total CO <sub>2</sub> e (g/kg dry biomass/100 km)	5.42

emissions for recovery of straw/stover and its transport per 100 km. These figures were used in this study. We note that these values are not critical to the study, since the emissions associated with harvesting and transport of agricultural residues have a minor contribution in the overall life cycle assessment of emissions (see, for example, European Council for Automotive R&D 2006; Mann and Spath 1997; and Spatari et al. 2005).

In this study the impact of straw/stover recovery on soil carbon levels was taken as zero. Hartmann (1999) found no reduction in carbon levels in black soils in western Canada after years of straw recovery. Henderson (2000) also reported no impact on soil carbon for the recovery of agricultural residues in Western Canada. Mann and Spath (1997) showed a wide variety of impact, from a loss of 4.5 to a gain of 40.3 Mg/ha for woodchip production from purpose-grown energy crops. Studies that have shown that soil carbon can be increased through improved practices, including intensive cropping systems, reduced tillage, improved crop nutrition, and perennial vegetation. These studies have noted that the effect is variable and finite, i.e., soil carbon reaches a new level and stabilizes, so that the impact is one time and not ongoing (Grant et al. 2001; Izaurralde et al. 2001; Janzen et al. 2001).

Note that transport distance is a function of three key variables:

- Gross yield of agricultural residues in the area from which biomass is drawn for a processing plant: the amount of residue produced per total area in a region. Note that total area includes all noncrop uses of land.
- The fraction of that residue that is sold to a biomass processing plant. We refer to biomass gross yield times the fraction sold to a biomass processing plant as biomass gross availability, in t/ha.
- The size of the processing plant.

In this study we have calculated transportation-related emissions assuming a biomass gross availability of 0.21 t/overall ha in the area from which biomass is drawn. This is equivalent to a 50% fraction of straw being available from a western Canadian grain region (Kumar et al. 2003) and a 25% yield of corn stover in the U.S. corn belt (Aden et al. 2002).

Biomass projects have competing cost elements: processing cost per unit of throughput decreases with increasing size, while the delivered cost of biomass increases because of increased transportation distance. The competition between these two cost factors leads to an optimum processing size at which the cost of produced energy is minimized (Ghafoori et al. 2005; Jenkins 1997; Kumar et al. 2003; Larson and Marisson 1997; Nguyen and Prince 1996; Overend, 1982; Rodrigues et al. 2003; and Searcy and Flynn, 2008). Searcy and Flynn (2008) show that optimum size is a function of biomass availability and processing cost, and for most values of these two factors the profile of cost vs. plant size flattens near the optimum. This means that the cost of producing energy from biomass initially changes slowly for sizes smaller than the theoretical optimum. A cost 3% higher

**Table 3** Size of processing plant and average transport distance for biomass processing cases.

	Plant size at theoretical optimum	Plant size corresponding to 103% of minimum (optimum) cost					
	dry t/d <sup>b</sup>	dry t/d <sup>b</sup>	ML/yr or MWe	MWh/dry t or L/dry t	MJ product/dry t	Average transport distance (km)	Transport emissions (g CO <sub>2</sub> e)
Ethanol	6750	3250	340	317 <sup>c</sup>	6.7	160	27.4/L
Ethanol + power <sup>a</sup>	—	—	68	—	8.7	—	—
FT	12750	6250	450	221 <sup>d</sup>	8.1	220	53.9/L
Direct comb. <sup>a</sup>	4375	2100	135	1.62 <sup>c</sup>	6.7	130	4.35/kWh
BIGCC <sup>a</sup>	11000	5250	470	2.00 <sup>f</sup>	7.2	200	5.42/kWh

<sup>a</sup>Power values are gross power production. Net power to grid is 26 MW (ethanol case), 124 MW (direct combustion), and 432 MW (BIGCC). Ethanol power output taken as the average from three studies: Aden et al. 2002; McAloon et al. 2000; and Wooley et al. 1999.

<sup>b</sup>Searcy and Flynn 2008.

<sup>c</sup>Aden et al. 2002.

<sup>d</sup>Consistent with Wright and Brown 2007; Larson et al. 2006; Prins et al. 2004; and Hamelinck et al. 2004.

<sup>e</sup>Based on an electrical efficiency of 32% at 135 MW.

<sup>f</sup>Based on 47% efficiency, and is consistent with Craig and Mann, 1996; Uddin and Barreto, 2007.

than the minimum, an arbitrarily chosen increase, corresponds to a plant size about one-half of the size at the theoretical optimum size. Plant sizes below this lead to a rapid increase in cost. Based on this prior work, in this study we have calculated transportation distances based on a plant size that achieves a cost 3% over optimum size.

A second impact of plant size occurs with direct combustion for electrical power, since plant efficiency is a function of plant size for smaller power plants (Flynn and Kumar 2005; Matvinchuk 2002; Stennes and McBeath 2005; van den Broek et al. 1995). In this work we assume a linear relationship between efficiency ( $MW_{elec}/MW_{thermal}$ ), ranging from 20% at 9 MW to 38.5% at 200 MW and higher, with the latter value corresponding to the reported efficiency of the Alholmens power plant (Flynn and Kumar 2005).

Table 3 shows the theoretical optimum size, the plant size used in this study, the conversion efficiency, the average transportation distance, and the transport emissions for each of the four biomass processing schemes evaluated in this study. As noted above, emissions from the transportation of biomass make a minor contribution to the overall LCA emissions comparison between biomass processing and the “business as usual” case.

## RESULTS

### Emissions for Electricity from Coal vs. Direct Combustion and BIGCC of Agricultural Residues

Kumar et al. (2003) reported emissions from a 450 MWe pulverized coal-fired boiler in Alberta as 968 g/kWh, a figure that includes emissions of methane from exposed surface-mined coal. The power plant is located at the coal mine, and hence transport emissions are negligible. In this study we adjust this number to 886 g/kWh to account for the improved efficiency of supercritical coal power plants relative to pulverized coal subcritical plants (EPCOR 2007). Natural Resources Canada (2006) cites a range from 729 to 919 g/kWh for

**Table 4** LCA emissions from power production from coal and straw/stover in g CO<sub>2</sub>e/kWh.

	Coal	Biomass direct combustion	BIGCC	(Coal – Direct combustion)	(Coal – BIGCC)
Production and harvesting of biomass	NA	51.7	41.9	–51.7	–41.9
Transport of biomass	NA	4.35	5.42	–4.35	–5.42
Extraction, transport, and power production from coal	886	NA	NA	886	886
Biomass power production	NA	0	0	0	0
Total	886	56.0	47.3	830	839

coal-fired power plants, while the comparable value from Environment Canada (2007) for an Alberta, Canada, surface mining plant is 836 g/kWh, and from Spath et al. (1999) for a new generation U.S.-based surface mining coal power plant is 941 g/kWh. The European Council for Automotive R&D (2006) cites a value of 873 g/kWh. All of these values are close to the value used in this study, 886 g/kWh, and within the cited accuracy of most LCA studies.

Most studies consider emissions relating to the production of power from delivered biomass to be negligible or zero (European Council for Automotive R&D, 2006; Kumar et al. 2003; Larson et al. 2006). Spath and Mann (2004) cite fossil fuel usage in a biomass direct combustion power plant as 1% that of a coal-fired plant. Mann and Spath (1997) developed a highly detailed analysis of a BIGCC power plant assuming future improvements in technology, and from this study we can conclude that there are only negligible incremental emissions directly resulting from plant operation, as compared to supercritical coal power generation. We follow the practice of most studies and treat emissions from power production from biomass as negligible relative to coal-fired power plant emissions. Table 4 shows the relative LCA emissions for the three technologies of power production and the incremental difference between coal and each of the biomass-based technologies.

### Emissions from Gasoline vs. Ethanol from Agricultural Residues

As noted above, emissions for the exploration and discovery of oil are negligible in an overall LCA analysis of emissions for the production of transportation fuels from oil. Many studies have reported a wide range of values for the extraction, transport, and refining of petroleum. Gasoline contains approximately 640 g carbon/L, producing 2350 g CO<sub>2</sub> (U.S. Environmental Protection Agency 2007). The difference in production of N<sub>2</sub>O during combustion of gasoline or a gasoline-ethanol blend is considered to have a negligible impact. Lewis (1997) specifically notes that the type of processing used to produce gasoline is not significant within the overall precision of the LCA, and further that the impact of emissions of CH<sub>4</sub> and NO<sub>x</sub> from extraction, transport, and refining is negligible relative to CO<sub>2</sub> emissions. This latter observation is supported by the findings of Furuholt (1995), Beer et al. (2002), and Sheehan et al. (1998). CO<sub>2</sub> emissions in g/L from gasoline production are reported at 135 (Facanha and Horvath 2007), 181 (Pierru 2007), 200 (Furuholt 1995), 321 (Lewis 1997), 402 (European Council for Automotive R&D 2006), 455 (Choudhury et al. 2002), 560 (Hu et al. 2004) and 639 (Levelton 2000), of which 60 g/L were attributable to leaks and flaring. The GHG emissions found by (S&T)<sup>2</sup> Consultants Inc. et al. (2008) using GHGenius and GREET models gave an average of 292 g CO<sub>2</sub>e/L for crude oil production, 460 g/L for crude oil refining, with a total of 750 g CO<sub>2</sub>e/L gasoline. Fleming et al. (2006) noted that although gasoline and diesel well-to-wheel processes are well established, there is



**Table 5** Emissions from the production of ethanol via enzymatic hydrolysis (Tyson, 1993) in g/L ethanol.

Stressor	Air emissions	Equivalent emissions
CO <sub>2</sub> (fossil)	26.9	26.9
CH <sub>4</sub>	0.00272	0.0571
N <sub>2</sub> O	0	0
Total fossil CO <sub>2</sub> e (g/L ethanol)		27.0

still a significant amount of variability in studies of production emissions. Variable transportation distance and quality of oil and produced gasoline and diesel are all factors, but as well there are numerous saleable products in an oil refinery and allocation of energy use and emissions to specific products is complicated and imprecise. In this study we use the average of the values presented above, 376 g CO<sub>2</sub>/L. We note that the major emissions from gasoline come from the use of the fuel itself, and the variance in reported emissions during extraction, transport, and refining are small compared to the carbon content of the fuel itself.

Tyson (1993) did a detailed analysis of emissions from a lignocellulosic ethanol plant using 1800 dry t/d of grasses and short rotation trees to produce 300 ML/yr of denatured ethanol and 17 MWe of power for export to the grid from combustion of the lignin fraction. Overall emissions of fossil CO<sub>2</sub>e are very small compared to the CO<sub>2</sub>e of the produced ethanol, 1940 g/L. Tyson’s values are shown in Table 5. Similar results were found by Spatari et al. (2005), Sheehan et al. (2004), and the European Council for Automotive R&D (2006). All these studies found CH<sub>4</sub> and N<sub>2</sub>O emissions to be negligible, as did Beer et al. (2002), Sheehan et al. (1998), and Furuholt (1995). Kadam (2002) reported a similar value for CO<sub>2</sub> emissions for ethanol production from sugar cane, but a tenfold higher level of methane emissions, while Fu et al. (2003) showed CO<sub>2</sub> emissions about twice as high for the production of ethanol from balsam fir. MacLean et al. (2004) note that ethanol has many alternative production options (feedstocks and conversion processes), and therefore the precision of results for an LCA analysis is less precise than for gasoline. Note, however, that fossil CO<sub>2</sub> emissions from the production of ethanol are in the order of 1% of the value of CO<sub>2</sub> emissions from gasoline, so the uncertainty is not significant.

Note that byproduct lignin is used in our study to produce power, and a surplus is available for export to the grid. Since the lignocellulosic ethanol plant would operate on a continuous basis, we treat the “business as usual” case as coal-fired power with an emission of 886 g/kWh, as discussed above. Table 6 shows the relative LCA emissions for gasoline and lignocellulosic ethanol and the difference between the two on an energy equivalent basis of one L of ethanol to 0.66 L of gasoline.

**Table 6** LCA emissions from 0.66 L gasoline vs. 1 L ethanol from straw/stover in g CO<sub>2</sub>e/L ethanol.

	0.66 L Gasoline	Ethanol	(Gasoline – Ethanol)
Production & harvesting of biomass	NA	264	–264
Transport of biomass	NA	27.4	–27.4
Extraction, transport, and refining of oil	250	0	250
Production of ethanol	NA	27.0	–27.0
Consumption of fuel	1550	0	1550
Production of electrical power	NA	–576	576
Total	1800	–258	2060

### Emissions from Diesel from Petroleum vs. Fischer Tropsch Processing of Syngas from Biomass

As noted above for gasoline, emissions for the exploration and discovery of oil are negligible and the emissions from diesel fuel usage are far higher than emissions during refining and transport. Diesel contains approximately 734 g carbon/L, producing 2690 g CO<sub>2</sub>. As referenced above, Fischer Tropsch diesel is sufficiently close in properties to diesel from petroleum that no significant differences in emissions during combustion would occur. There is again a very high variance in reported emissions for the production of diesel, as noted by Fleming et al. (2006). CO<sub>2</sub>e emissions in g/L are reported as 120 (Furuholt 1995), 165 (Sheehan et al. 1998), 381 (Choudhury et al. 2002), 429 (Beer et al. 2002), 481 (European Council for Automotive R&D 2006), 560 (Singh et al. 1998), and 612 (Fleming et al. 2006). Some but not all studies report methane emissions, in g/L and g CO<sub>2</sub>e/L of, of 1.3 and 27.3 (Beer et al. 2002), 1.46 and 30.7 (Sheehan et al. 1998), and 8.30 and 174.3 (Singh et al. 1998). Only Sheehan et al. (1998) reports N<sub>2</sub>O emissions of 0.0485 g/L, equivalent to 15.0 g CO<sub>2</sub>e/L. We use a blended value of 400 g CO<sub>2</sub>e/L for diesel transport and refining, noting that the variance in values for refining is again small in relation to the fossil CO<sub>2</sub> released during combustion.

There are fewer studies of Fischer Tropsch diesel than of ethanol fermentation, and as a result data on emissions is limited. Fischer Tropsch plants can be configured in a variety of ways, e.g., to produce some transportation fuel and power from unreacted gas or to maximize the production of a naphtha or diesel fraction. They can also use a variety of initial feedstocks, e.g., coal, natural gas, or biomass. This study is based on importing power to the FT plant to maximize the production of syndiesel. (S&T)<sup>2</sup> Consultants (2006) studied syndiesel production from wood; from their data, total emissions are 322 g CO<sub>2</sub>e/L, a value that includes biomass harvest and transport. Imported power consumption during production and the production process itself have emissions of 91 g CO<sub>2</sub>e/L. Abbott et al. (2006) studied a 75,000 bbl/d FT plant using a natural gas feedstock. From their data the value for emissions from the FT production step, including imported power, are 231 g CO<sub>2</sub>e/L. Finally, data from a study by The European Council for Automotive R&D (2007) was adjusted to increase the emissions associated with power generation to reflect an Alberta average grid emissions level of 761 g CO<sub>2</sub>e/kWh (Tampier et al. 2004), higher than the value in the European study that assumed a significant amount of nuclear power in the generation pool. This leads to a calculated emission of 339 g CO<sub>2</sub>e/L from the FT production process, including imported power. In this study we use a value of 220 g CO<sub>2</sub>e/L, the average of the above values; we note again that the variance in values for emissions from FT production is small in relation to the fossil CO<sub>2</sub> released by combustion of diesel from oil. Table 7 shows the relative LCA emissions for diesel and FT syndiesel and the difference between the two.

**Table 7** LCA emissions from diesel vs. syndiesel from straw/stover in g CO<sub>2</sub>e/L.

	Diesel	FT syndiesel	Difference (Diesel – FT Syndiesel)
Production and harvesting biomass	NA	380	–380
Transport of biomass	NA	53.9	–53.9
Extraction, transport, and refining of oil	400	NA	400
Production of FT syndiesel	NA	220	–220
Consumption of fuel	2690	0	2690
Total	3090	654	2440

**Table 8** Summary and comparison of avoided emissions.

	Avoided emissions (g CO <sub>2</sub> e)	Avoided emissions (kg CO <sub>2</sub> e/t dry biomass input)
Direct combustion	830/kWh	1345
BIGCC	839/kWh	1680
Ethanol production	2060/L	650
FT synthesis	2440/L	540

**Comparison of LCA Avoided Emissions per Unit of Biomass Input**

The yield data from Table 3 can be combined with the values for LCA emissions reductions for each of the four processes to calculate avoided emissions per unit of biomass input, shown in Table 8. On the basis of emissions reductions alone, production of BIGCC from straw achieves the greatest reduction in CO<sub>2</sub>e, and syndiesel the least.

**DISCUSSION**

A world moving towards significant adoption of low carbon or renewable energy needs to have a clear picture of the relative cost of the myriad of choices available. Two key factors are involved. First, what is the incremental cost of adopting a renewable energy technology relative to a “business as usual” case, usually continued use of a fossil fuel? Second, what is the avoided GHG emissions realized from adopting the technology? In this work we have taken one abundant biomass resource, straw/corn stover, and evaluated avoided emissions from four different processing routes.

A common problem in evaluating competitive technologies is the difference in degree of development, and hence reliability of data, for the technologies, and this is well illustrated in the four straw processing alternatives in this study. Large-scale direct combustion of biomass is commercially available and practiced today. Enzymatic hydrolysis of straw/stover followed by fermentation to ethanol is just now being applied at a commercial scale, and detailed cost and design data is not available in the literature from these projects. BIGCC and the production of FT diesel from biomass have not been applied even at a modest demonstration scale. This impact is moderated by the observation in this study that variance in estimates of emissions from processing of coal to power either end product are small compared to the large value of avoided emissions that arises from the substitution of biomass for a fossil fuel. The avoided emissions shown in Table 8 overwhelmingly arise from the avoidance of the fossil fuel itself, while differences in emissions during processing are minor. Further analysis may reduce the range of estimated values for GHG emissions during processing of fossil fuels and biomass, especially for biomass processes that have not been built at a demonstration scale, but the impact on the conclusions of this study are likely to be minor.

Scale (i.e., plant size) has a significant impact on the cost of energy produced from biomass and has two impacts on the emissions. One emissions impact is relatively minor: transportation distance increases with plant size, but emissions from transport of biomass to a processing plant are small compared to the overall avoided emissions. A second emissions impact is more significant for one technology: the efficiency of producing electricity from the direct combustion of biomass falls significantly at plant size smaller than 200 MW. The Alholmens 240 MW power plant has an electrical generating efficiency (LHV) of 38.5%

(Flynn and Kumar 2005), while typical values for a 25 MW plant burning wood are 25–28% (Matvinchuk, 2002; van den Broek et al. 1995). The lower efficiency for smaller plants arises from heat loss as the ratio of firebox volume to surface area decreases. In this study, plant sizes were set to have a product cost 3% higher than a theoretical optimum minimum cost, which tends to occur at a plant size of about 50% of the theoretical optimum size (Searcy and Flynn 2008).

Avoided GHG emissions per tonne of biomass input are far higher for power generation than for the production of transportation fuels. This is not sufficient to make a case for favoring power generation from biomass. The key question is the incremental cost of achieving a unit reduction in carbon emissions, which requires the integration of both cost and emission data. This is the subject of future work.

## CONCLUSIONS

Based on an analysis of a wide range of studies, avoided GHG emissions for four processes for converting straw or corn stover to usable energy are calculated relative to a western North American “business as usual” case. Net avoided emissions for the four technologies are as follows:

- Direct combustion to produce electrical power: 830 g CO<sub>2</sub>e/kWh, or 1,345 kg CO<sub>2</sub>e/dry t of straw/stover
- BIGCC to produce electrical power: 839 g CO<sub>2</sub>e/kWh, or 1,680 kg CO<sub>2</sub>e/dry t of straw/stover
- Enzymatic hydrolysis for the production of ethanol: 2,060 g CO<sub>2</sub>e/L, or 650 kg CO<sub>2</sub>e/dry t of straw/stover
- FT synthesis for the production of syndiesel: 2,440 g CO<sub>2</sub>e/L, or 540 kg CO<sub>2</sub>e/dry t of straw/stover

The largest impact on avoided emissions arises from substitution of biomass for fossil fuel. Relative to this, the impact of emissions from processing of fossil fuel, e.g., refining of oil to produce gasoline or diesel, and processing of biomass to produce electricity or transportation fuels, is minor.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from Canada’s Natural Sciences and Engineering Research Council, EPCOR, and the Poole Family; all conclusions are the authors’.

## REFERENCES

- Abbott, R., E. Casey, E. Esen, D. Smith, B. Burke, B. Nguyen, S. Tam, P. Wornach, M. Alam, J. Song, J. Szybist, R. Acharya, V. Zello, D. Morris, P. Flynn, S. Kirby, K. Bhatia, J. Gonder, Y. Wang, W. Liu, H. Meng, S. Velu, J. Shen, W. Gu, W. Bickford, C. Song, C. Wang, and A. Boehman. 2006. *Evaluation of ultra clean fuels from natural gas*. Final Report, September 1999–February 2006, Volume 1. A collaboration of ConocoPhillips, Nexant, Inc., and Pennsylvania State University for the United States Department of Energy, Cooperative agreement DE-FC26-01NT41098.
- Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace. June 2002. *Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute*

- acid prehydrolysis for corn sStover*. NREL/TP-510-32438, National Renewable Energy Laboratory, Golden, Colorado.
- Alberta Environment. 2007. *Specified gas reporting standard*. Prepared by Evaluation and Reporting Section of the Environmental Monitoring and Evaluation Branch, 978-0-7785-5476-9. <http://www.environment.gov.ab.ca/info/library/7759.pdf> (accessed August 8, 2007).
- Beaudry-Losique, J. 2007. U.S. Department of Energy Biomass Program: Growing a robust biofuels economy. Presentation, Venture Capital Forum, August 21–22. [http://www1.eere.energy.gov/office\\_eere/pdfs/biomass.pdf](http://www1.eere.energy.gov/office_eere/pdfs/biomass.pdf) (accessed July 7, 2008).
- Beer, T., T. Grant, D. Williams, and H. Watson. 2002. Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles. *Atmospheric Environment* 36: 753–763.
- Choudhury, R., R. Wurster, T. Weber, J. Schindler, W. Weindorf, M. Miller, N. Brinkman, A. Armstrong, D. Rickeard, G. Jersey, M. Kerby, H. Kheshgi, J. Robbins, D. Le Breton, and O. Dautrebande. 2002. GM well-to-wheel analysis of energy use and greenhouse gas emissions of advanced fuel/vehicle systems—A european study. <http://www.lbst.de/gm-wtw> (accessed on January 8, 2007).
- Craig, K., and M. Mann. 1996. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems. NREL/TP-430-21657, National Renewable Energy Laboratory, Golden, Colorado.
- Environment Canada. 2007. National inventory report, greenhouse gas sources and sinks in Canada 1990–2005. The Canadian government's submission to the United Nations framework convention on climate change.
- EPCOR. 2007. Advanced coal technology working group presentation, presented by Doug Topping, March 29, 2007. [http://www.epa.gov/air/caaac/coaltech/2007\\_03b\\_epcor.pdf](http://www.epa.gov/air/caaac/coaltech/2007_03b_epcor.pdf) (accessed August 16, 2007).
- European Council for Automotive R&D. 2006. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Joint report by European Council for Automotive R&D (EUCAR), Conservation of Clean Air and Water in Europe (CONCAWE) and the Joint Research Council (JRC). Version 2b.
- European Council for Automotive R&D. 2007. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. Joint report by European Council for Automotive R&D (EUCAR), Conservation of Clean Air and Water in Europe (CONCAWE) and the Joint Research Council (JRC). Version 2c.
- Facanha, C., and A. Horvath. 2007. Evaluation of life-cycle air emission factors of freight transportation. *Environmental Science and Technology* 41: 7138–7144.
- Fleming, J., S. Habibi, and H. MacLean. 2006. Investigating the sustainability of lignocellulosic-derived fuels for light-duty vehicles. *Transportation Research Part D*, 11: 146–159.
- Flynn, P., and A. Kumar. 2005. Trip report: Site visit to Alholmens 240 MW power plant, Pietarsaari, Finland, August 29 to September 2, 2005. Prepared for the Biocap Canada Foundation and the Province of British Columbia.
- Fu, G., A. Chan, and D. Minns. 2003. Life cycle assessment of bio-ethanol derived from cellulose. *International Journal of LCA Studies* 8: 137–141.
- Furuholt, E. 1995. Life cycle assessment of gasoline and diesel. *Resources, Conservation, and Recycling* 14: 251–263.
- Ghafoori, E., P. Flynn, and J. Feddes. 2005. Pipeline vs. truck transport of beef cattle manure. Paper No. 054073, presented at the 2005 ASAE Annual International Meeting, Tampa Convention Center, Tampa, Florida, 17–20 July.
- Grant, R., N. Juma, J. Robertson, R. Izaurralde, and W. McGill. 2001. Long-term changes in soil carbon under different fertilizer, manure, and rotation: testing the mathematical model ecosys with data from the Breton Plots. *Soil Science Society of America Journal* 65: 205–214.
- Hartmann, M. 1999. Direct Seeding—Estimating the value of crop residues. Agdex 519–25. Alberta Agriculture, Canada.

- Henderson, S. for Levelton Engineering Ltd. 2000. Assessment of net emissions of greenhouse gases from ethanol-blended gasolines in Canada: Lignocellulosic feedstocks. Prepared for Agriculture and Agri-Food Canada (R2000-2).
- Hu, Z., F. Fang, D. Ben, G. Pu, and C. Wang. 2004. Net energy, CO<sub>2</sub> emission, and life-cycle cost assessment of cassava-based ethanol as an alternative fuel in China. *Applied Energy* 78: 247–256.
- Izaurrealde, R., W. McGill, J. Robertson, N. Juma, and J. Thurston. 2001. Carbon balance of the Breton classical plots over half a century. *Soil Science Society of America Journal* 65: 431–441.
- Janzen, H., C. Campbell, R. Izaurrealde, B. Ellert, N. Juma, W. McGill, and R. Zentner. 2001. Management effects on soil C storage on the Canadian prairies. *Soil & Tillage Research* 47: 181–195.
- Jenkins, B. M. 1997. A comment on the optimal sizing of a biomass utilization facility under constant and variable cost scaling. *Biomass and Bioenergy* 13: 1–9.
- Kadam, K. 2002. Environmental benefits on a life cycle basis of using bagasse-derived ethanol as a gasoline oxygenate in India. *Energy Policy* 30: 371–384.
- Kumar, A., J. Cameron, and P. Flynn. 2003. Biomass power cost and optimum plant size in western Canada. *Biomass and Bioenergy* 24: 445–464.
- Laohalidanond, K., J. Heil, and C. Wirtgen. 2006. The production of synthetic diesel from biomass. *KMITL Science Technology Journal* 6: 1.
- Larson, E., S. Consonni, R. Katofsky, K. Iisa, J. Frederick, Jr. 2006. A cost-benefit assessment of gasification-based biorefining in the Kraft pulp and paper industry. U.S. Department of Energy and American Forest and Paper Association, contract DE-FC26-04NT42260.
- Larson, E., and C. Marrison. 1997. Economic scales for first-generation biomass-gasifier/gas turbine combined cycles fueled from energy plantations. *Journal of Engineering for Gas Turbines and Power* 119: 285–290.
- Levelton Engineering Ltd. 2000. Assessment of net emissions of greenhouse gases from ethanol-blended gasolines in Canada: Lignocellulosic feedstocks, Cross-Sectoral Policy Development Division, Industry Performance and Analysis Directorate, Policy Branch, Agriculture and Agri-Food Canada.
- Lewis, C. 1997. Fuel and energy production emissions, MEET Project: Methodologies for estimating air pollutant emissions from transport. Task 3.4, Deliverable 20, Contract No. ST-96-SC.204. Project funded under the European Commission under the Transport RTD program of the 4th framework program.
- MacLean, H., L. Lave, and W. Griffin. 2004. Alternative transport fuels for the future. *International Journal of Vehicle Design* 35: 27–49.
- MacLean, H., L. Lave, R. Lankey, and S. Joshi. 2000. A life cycle comparison of alternative automobile fuels. *Journal of the Air & Waste Management Association* 50: 1769–1779.
- Mann, M., and P. Spath. 1997. Life cycle assessment of a biomass gasification combined-cycle power system. DE-AC36-83CH10093, National Renewable Energy Laboratory, Golden, Colorado.
- Matvinchuk, D. 2002. Plant Manager—Whitcourt Biomass Power Generating Station, Alberta, Canada. Personal communication.
- McAloon, A., F. Taylor, W. Yee, K. Ibsen, and R. Wooley. 2000. Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks. National Renewable Energy Laboratory, Golden, Colorado, NREL/TP-580-28893. A joint study sponsored by the U.S. Department of Agriculture and the U.S. Department of Energy.
- Natural Resources Canada. 2006. Canada's Energy Outlook: The reference case 2006. Analysis and Modeling Division. <http://www.nrcan.gc.ca/com/resoress/publications/peo/peo2006-eng.pdf> (accessed December 11, 2007).
- Nguyen, M., and R. Prince. 1995. A simple rule for bioenergy conversion plant size optimization: bioethanol from sugar cane and sweet sorghum. *Biomass and Bioenergy* 10: 361–365.
- Oak Ridge National Laboratory. [http://bioenergy.ornl.gov/papers/misc/energy\\_conv.html](http://bioenergy.ornl.gov/papers/misc/energy_conv.html) (accessed August 11, 2007).

- Overend, R. 1982. The average haul distance and transportation work factors for biomass delivered to a central plant. *Biomass* 2: 75–79.
- Permolex International, LP. <http://www.permolex.com/pdf/EthanolSpecs.pdf> (accessed July 10, 2008).
- Pierru, A. 2007. Allocating the CO<sub>2</sub> emissions of an oil refinery with Aumann-Shapely prices. *Energy Economics* 29: 563–577.
- Prins, M., K. Ptasiński, and F. Janssen. 2004. Exergetic optimization of production process of Fischer-Tropsch fuels from biomass. *Fuel Processing Technology* 86: 375–389.
- Rodrigues, M., A. Walter, and A. Faaij. 2003. Techno-economic analysis of co-fired biomass integrated gasification/combined cycle systems with inclusion of economics of scale. *Energy* 28: 1229–1258.
- (S & T)<sup>2</sup> Consultants Inc. 2006. The addition of palm oil biodiesel and coal derived FT distillate to GHGenius. Prepared for Natural Resources Canada.
- (S&T)<sup>2</sup> Consultants Inc., Cheminfo Services Inc., H. MacLean, and Fugacity Technology Consulting. 2008. Sensitivity analysis of bioethanol LCA models to determine assumptions with the greatest influence on outputs.
- Santer, B., C. Mears, F. Wentz, K. Taylor, P. Glecker, T. Wigley, T. Barnett, J. Boyle, W. Bruggemann, N. Gillett, S. Klein, G. Meehl, T. Nozawa, D. Pierce, P. Stott, W. Washington, and M. Wehner. 2007. Identification of human-induced changes in atmospheric moisture content. *Proceedings of the National Academy of Sciences (U.S.A.)* 104: 15248–15253.
- Searcy, E., and P. Flynn. 2008. The impact of biomass availability and processing cost on optimum size and processing technology selection. *Applied Biochemistry and Biotechnology*. In press.
- Searcy, E., P. Flynn, E. Ghafoori, A. Kumar. 2007. The relative cost of biomass energy transport. *Applied Biochemistry and Biotechnology* 136–140: 639–652.
- Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2004. Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology* 7: 117–146.
- Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, H. Shapouri. 1998. Life cycle inventory of syndiesel and petroleum for use in an urban bus. Final Report, NREL/SR-580-24089, prepared for the U.S. Department of Energy's Office of Fuels Development and U.S. Department of Energy's Office of Energy, May 1998. NREL, Golden, Colorado.
- Singh, M., R. Cuenca, J. Formento, L. Gaines, B. Marr, D. Santini, M. Wang, S. Adelman, D. Kline, J. Mark, J. Ohi, N. Rau, S. Freeman, K. Humphreys, and M. Placet. 1998. Total energy cycle assessment of electricity and conventional vehicles: An energy and environmental analysis, Vol. 1: Technical report. Prepared by Argonne National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy.
- Spatari, S., Y. Zhang, and H. Maclean. 2005. Life cycle assessment of switchgrass and Corn Stover-Derived Ethanol-Fueled Automobiles. *Environmental Science and Technology* 39: 9750–9758.
- Spath, P., and M. Mann. 2004. Biomass power and conventional fossil systems with and without CO<sub>2</sub> sequestration—Comparing the energy balance, greenhouse gas emission and economics. NREL/TP-510-32575, National Renewable Energy Laboratory, Golden Colorado.
- Spath, P., M. Mann, and D. Kerr. 1999. Life cycle assessment of coal-fired power production. NREL/TP-570-25119, National Renewable Energy Laboratory, Golden, Colorado.
- Stennes, B., and A. McBeath. 2005. Bioenergy options for woody feedstock. Final draft report. Pacific Forestry Centre, Canadian Forestry Service, Victoria, B.C., Canada. [http://mpb.cfs.nrcan.gc.ca/research/workshops/8-37/Stennes-McBeath\\_e.pdf](http://mpb.cfs.nrcan.gc.ca/research/workshops/8-37/Stennes-McBeath_e.pdf) (accessed July 10, 2008).
- Tampier, M., D. Smith, E. Bibeau, and P. Beauchemin. 2004. Identifying environmentally preferable uses for biomass resources, Stage 2 report: Life-cycle GHG emission reduction benefits of selected feedstock-to-product threads. Prepared for Natural Resources Canada and the National Research Council of Canada by Envirochem Services Inc, North Vancouver, British Columbia.

- Tyson, S. 1993. Fuel cycle evaluations of biomass-ethanol and reformulated gasoline. Prepared for the Office of Transportation Technologies and the Office of Planning and Assessment, Assistant Secretary for Energy and Renewable Energy, U.S. DOE by the NREL, Golden, Colorado. NREL/TP-463-4950. November 1993.
- Uddin, S., and L. Barreto. 2007. Biomass-fired cogeneration systems with CO<sub>2</sub> capture and storage. *Renewable Energy* 32: 1006–1019.
- United States Environmental Protection Agency (U.S. EPA). <http://www.epa.gov/otaq/climate/420f05001.htm#carbon> (accessed July 12, 2007).
- U.S. Department of Energy. <http://www.energy.gov/news/4827.htm> (accessed July 9, 2008).
- Van den Broek, R., A. Faaij, and A. Wijk. 1995. Biomass combustion power generation technologies. Background report 4.1 for the EU Joule II + Project: Energy from biomass: an assessment of two promising systems for energy production. Department of Science, Technology and Society, Utrecht University, Report 95029.
- Wright, M., and R. Brown. 2007. Comparative economics of biorefineries based on the biochemical and thermochemical platforms. Society of Chemical Industry and John Wiley & Sons, Ltd. Published online in Wiley Interscience ([www.interscience.wiley.com](http://www.interscience.wiley.com)).